SURVIVABILITY · SUSTAINABILITY · MOBILITY
SCIENCE AND TECHNOLOGY
SOLDIER SYSTEM INTEGRATION

TECHNICAL REPORT
NATICK/TR-95/034

AD_______________

OSMOTIC DEHYDRATION AND ITS APPLICATIONS IN NUTRIENT INFUSION OF VARIOUS FOODS

By
Joseph Cohen
Tom C. S. Yang

September 1995

FINAL REPORT
March 1995 - June 1995

Approved For Public Release; Distribution Unlimited

U.S. ARMY SOLDIER SYSTEMS COMMAND (PROV)
NATICK RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
NATICK, MASSACHUSETTS 01760-5018

SUSTAINABILITY DIRECTORATE

DISCLAIMERS

The findings contained in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of trade names in this report does not constitute an official endorsement or approval of the use of such items.

DESTRUCTION NOTICE

For Classified Documents:

Follow the procedures in DoD 5200.22-M, Industrial Security Manual, Section II-19 or DoD 5200.1-R, Information Security Program Regulation, Chapter IX.

For Unclassified/Limited Distribution Documents:

Destroy by any method that prevents disclosure of contents or reconstruction of the document.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1995	FINAL March 1995 - June 1995

4. TITLE AND SUBTITLE
OSMOTIC DEHYDRATION AND ITS APPLICATIONS IN NUTRIENT INFUSION OF VARIOUS FOODS

5. FUNDING NUMBERS
PE 0708045A
PR DE71

6. AUTHOR(S)
Joseph Cohen and Tom C. S. Yang

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Soldier Systems Command(PROV)
Natick Research, Development and Engineering Center
Kansas St. ATTN:AMSSC-WAA
Natick, MA 01760-5018

8. PERFORMING ORGANIZATION REPORT NUMBER
NATICK/TR-95/034

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The feasibility of osmotic drying of various foods, pitted cherries, whole blueberries and cubed carrots, was demonstrated. The feasibility of applying the osmotically-induced migration of compounds through the membrane of food samples was also examined. The osmotic solutions included sucrose, dextrose, maltose, honey, maltodextrin and salt. Drying was accomplished at atmospheric pressure at room and boiling temperatures and under vacuum at room temperature. In some experiments, final drying was achieved in a forced air dryer.

14. SUBJECT TERMS
OSMOSIS, FORCED AIR DRYING, DRYING, SUCROSE, MALTOSE, INFUSION, VACUUM INFUSION, HONEY, CARROTS, SUCROSE, NUTRIENTS, FOOD DEHYDRATION, CHERRIES, MEMBRANES

15. NUMBER OF PAGES
23

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

PREFACE

The data for this report were collected by investigators from the U.S. Army Soldier Systems Command ((SSCOM), Natick Research, Development and Engineering Center (NRDEC) from 1 March 1995 to 30 June 1995. This report describes experiments done with pitted cherries, whole blueberries and cubed carrots that demonstrated the feasibility of osmotic drying. Also demonstrated was the osmotically induced migration of caffeine through the membranes of the food samples. Various osmotic solutions were used. The solutions contained sucrose, dextrose, maltose, honey , maltodextrin and sodium chloride. Drying was accomplished under different conditions including room and boiling temperatures, at atmospheric pressure and under vacuum.

The investigation was conducted by the Advanced Foods Branch, Sustainability Directorate under project number DE 71.

Citation of trade names in this report does not constitute an official endorsement or approval of the use of such item.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of Margaret Robertson and Charles Roche of the Advanced Food Branch of the Sustainability Directorate, NRDEC.

OSMOTIC DEHYDRATION AND ITS APPLICATIONS IN NUTRIENT INFUSION OF VARIOUS FOODS

INTRODUCTION

The military services have a need for low and intermediate moisture foods of good nutrition and high sensory acceptability with a reduced cost of processing. Such foods will deliver a high density of nutrients, calories, etc. Osmotic dehydration, with the aid of vacuum infusion, is such a low cost operation that has many advantages. The infusing of additional nutrients into this type of food would further enhance the concentrated ration.

Freezing of foods, particularly fresh fruits and vegetables, uses much energy to freeze the large quantity of water that is present. Huxsoll (1982) noted that there would be a significant savings in energy costs if the food materials were concentrated prior to freezing. In addition to the energy savings, other advantages to water removal would be a savings in packaging and distribution costs and in maintaining good product quality.

Osmotic drying is a process in which water is removed from a food, such as fruit or vegetable pieces, by placing them in a hypertonic solution. Since the solution has a higher osmotic pressure than the food there is a driving force to remove water from the food. The cell wall will act as a semi-permeable membrane and allow some exchange of the solute between the solution and the food. Osmotic drying is therefore a simultaneous water and solute diffusion process.

Many authors have studied various aspects of osmotic drying: the solutes used, processing variables, combination process and quality of the final products.

The osmotic solutions to be used must have a low a_w, be harmless and have a pleasant or neutral flavor. Concentrated sucrose solutions of 50 to 70^o Brix have often been used. Contreras and Smyrl (1981) used corn syrup as the solute to concentrate apple rings. They observed that the mass of the apple rings could be reduced by 70% in this process. However, sodium chloride (NaCl) would make a good osmotic drying solution for vegetables. Adambounou et al. (1983) noted that its use with fruit imparted an undesirable salty flavor.

Although the most common osmotic agents are sucrose for fruits and NaCl for vegetables, other agents include glucose, fructose, lactose, maltodextrin and mixtures of the carbohydrates (Biswal and Le Maguer, 1969; Hawkes and Flink, 1978; Giangiacomo et al., 1987; Torregiani et al. 1987.)

A number of authors including Pinnavaia et al. (1983) and Andreotti et al. (1983)

used commercial syrups as the osmotic agent. Bolin et al. (1983) used high fructose corn syrup with apple pieces and noted the higher diffusivity as compared to sucrose. Ray (1960) explained this observed behavior by the conventional diffusion procedure. Chandrasekaran and King (1972) found that fructose also had a higher diffusion coefficient than sucrose and explained it by the smaller dimension of the monosaccharide molecule.

The quantity and the rate of water removal depends on numerous variables and processing parameters. The mass loss in the food is increased by using a greater solute concentration of the osmotic solution, increased immersion time, higher solution/food ratio, increased surface area of the food and the use of a low pressure system.

A number of investigators studied the effect of temperature and solute concentration on the osmosis kinetics. They include: Ponting et al. (1966); Farkas and Lazar (1969); Lerici et al. (1977); Hawkes and Flink (1978); Contreras and Smyrl (1981); Dalla Rosa et al. (1982); Andreotti et al. (1983) and Conway et al. (1983). In general these factors do affect the kinetics and should be studied.

The water and solutes transfer can be determined by simultaneously measuring the water loss and solid gain during the processing. Hawkes and Flink (1978) showed a simple method for doing this analysis. Changes in the A_W of the solution and the osmotically dried fruit were measured by Lerici, Dalla Rosa and Pinnavaia (1983) and Lenart and Flink (1984) as an index of the changes that occurred during the osmosis. A method of determining this is described.

The osmotically dried product can then be further dried, pasteurized or frozen (Ponting,1973; Dixon et al., 1976; Islam and Flink, 1982; Lerici, Dalla Rosa and Pinnavaia, 1983; Madarro et al.,1983; Maltini et al., 1983)

Lerici et al. (1983) and Adambounou and Castaigne (1983) noted that the water sorption isotherm is an important property of the food relative to drying as this determines the degree of drying required to obtain a stable product.

Some other advantages for osmotic drying as compared to other drying process include less changes to color and flavor because of heat damage, less discoloration of the fruit by enzymatic oxidative browning (Ponting et al., 1966 and Contreras and Smyrl, 1981). This will eliminate the need for using sulphur dioxide. Farkas and Lazar (1969) found the increased sugar content of the partially dried fruit gave a sweeter flavor in the processed fruit. Hawkes and Flink (1978) showed an increased sensory acceptability of apple slices that had been osmotically concentrated by sucrose solutions.

Lerici et al. (1985) studied different osmotic solutions, with and without added quantities of NaCl, and they found the NaCl addition increased the driving force of the drying process.

Osmotic drying can be used as an intermediate step in the air drying of fruits and vegetables (Flink, 1980; Kim and Toledo, 1987 and Lerici et al.,1985) or in freeze drying (Hawkes and Flink, 1978). Farkas and Lazar (1969) studied the process as an intermediate step in the freezing of apples and found that the apple quality was comparable to apples prepared by conventional dehydrofreezing.

Torreggiani et al. (1988) prepared intermediate moisture frozen apples, peaches and apricots by either osmotic drying or by combining osmotic drying with air drying and subsequent freezing. The color, texture and sensory scores showed that the osmotically dried, frozen fruits were acceptable.

Biswal et al. (1991) used aqueous solutions of NaCl as an intermediate step in freezing green beans. Organoleptic studies of color, hardness, texture, taste and overall acceptability indicated that the green beans were acceptable.

Complex carbohydrates play an important role in an ongoing project to incorporate performance-enhancing ingredients into military rations at the U.S. Army Natick RD&E Center. Osmotic processing provides a potential vehicle to infuse cselected ingredients into the food matrix, either through osmotic potential or pressure difference (hyper or hypobaric processes). Briggs et al. (1986) used vacuum infusion to produce calorically dense, low volume components for incorporation in operational rations.

Barrett (1986, 1987) investigated the factors that influence the penetration of particles into porous foods. Barrett et al. (1990) prepared a mathematical model that can be used to predict the vacuum infusion of suspension of food powders in fat into a porous food matrix of extruded starch crackers.

This paper will report on a number of osmotic drying studies performed with different products to determine the effect of processing parameters. The products used were pitted cherries, whole blueberries and cubed carrots.

The parameters studied were: Processing temperature, 20 C and 100 C; Osmotic molecule, sucrose, fructose, dextrose, maltodextrin, honey, salt; Concentration of solids in the osmotic solution, 50 to 80%; Ratio of osmotic solution to product, 2/1 to 4/1; Effect of pressure. Also studied was the ability of the process to infuse an added substance, (e.g. caffeine) into the product.

The presentation will be as a series of experiments.

Materials and Methods

A. Food Materials

a. Cherries

Individually Quick Frozen (IQF) sour cherries in sugar solution were used. They were approximately 1.0 to 1.35 cm in size with 22.9% solids. The cherries were thawed and the surface sugar was then rinsed off.

b. Blueberries

IQF whole blueberries in a bulk pack were used. They were approximately 0.6 to 1.0 cm in size with 14.1% solids. The blueberries were thawed before use.

c. Carrots

IQF cubed carrots in a bulk pack were used. They were approximately 0.8 to 1.0 cm in size with 11.7% solids. The carrots were thawed before use.

B. Criteria for Conclusions Pertaining to the Osmotic Processing

In all the studies the final solid content of the product was measured and compared to the unprocessed control. An increase in solid content indicates a loss of moisture and an uptake of solids from the osmotic solution. Moisture analyses were done with a Computrac™ Moisture Analyzer.

C. Equipment

a. Atmospheric Pressure Equipment

These series of experiments were performed in small circular aluminum pots with a bottom dimension of 14 cm diameter, a height of 12.7 cm, sloping upward to a top diameter of 17.8 cm. The pot had a capacity of approximately 2,000 cubic cm.

b. Vacuum Equipment

These experiments were performed in the apparatus shown in Fig. 1. This consists of a cylindrical plexiglass container with outlets and valves leading to the vacuum pump and the atmosphere. The product was placed in the chamber with the osmotic solution. The chamber was tightly sealed and the chamber evacuated to a pressure of 24 to 25 in Hg (81 to 84 kPa). The vacuum was maintained during the experiment. At the completion of the dwell time, the vacuum was released and the chamber emptied.

Experimental Procedure

A. Effect of dry substances on cherries.

Fifteen hundred grams of cherries was mixed with 165 g of either granulated sucrose or NaCl. The mixtures were stored in a refrigerator at 2 C for 24 hours. The cherries were separated from the liquid and rinsed. Four hundred and thirty grams

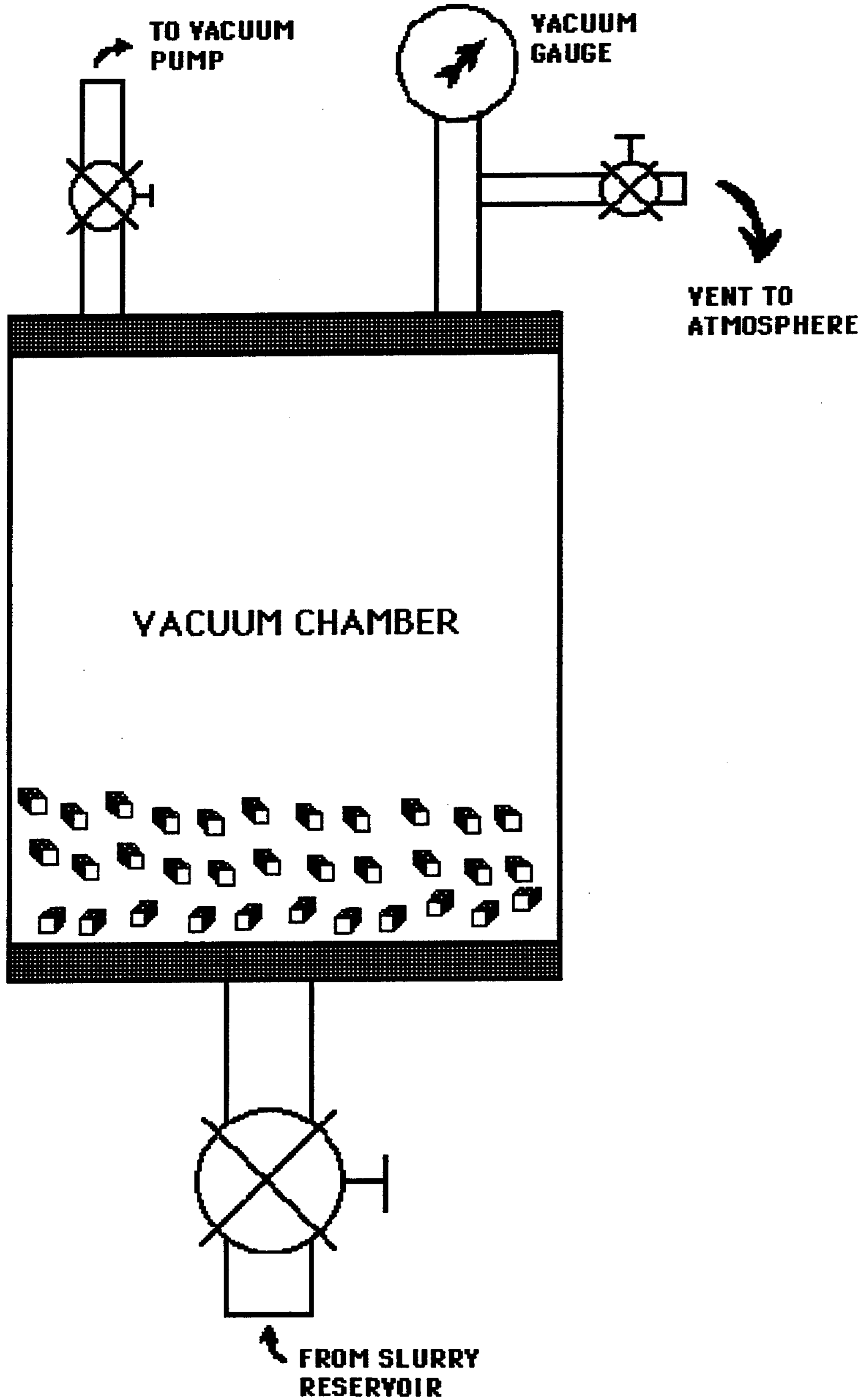

Figure 1 - VACUUM INFUSION DRYING APPARATUS

of either sucrose or NaCl was mixed with the drained cherries. During this second phase sucrose was added to the cherries that were previously mixed with the NaCl and the NaCl to the cherries that had been mixed with the sucrose. The new mixtures were replaced in the refrigerator for an additional 24 hours. The cherries were again separated from the liquid and rinsed. At the end of this time additional moisture was removed in a forced air dryer at 82 C for 4 hours. Table 1 shows the increased solids content.

Table 1 - Solid Content of Cherries as Function of Osmotic Solution

Solution	Mass, g, after 24 hrs	Mass, g, after 48 hrs	Percent Solids After Air Drying
NaCl, then Sucrose	1290	1190	58.6
Sucrose, then NaCl	1300	1160	53.4

Conclusions - The final recovery after air drying was approximately 500 g for both trials. Both sets of cherries tasted very salty. This showed that osmotic drying will work with either sucrose or NaCl despite its impracticality.

B. Effect of processing temperature with cherries

Three hundred grams of cherries were mixed with 600 g of an 80% sucrose solution. Two samples of the mixture were allowed to stand at room temperature for 24 and 48 hours. Two other samples were gently boiled with constant mixing for 30 and 60 minutes. At the end, the cherries were separated from the syrup and rinsed. The increase in solids content is shown in Table 2.

Table 2 - Solid Content of Cherries as Function of Processing Temperature

Process Temp, C	Time, Min	Final Mass, g	Final Percent Solids
ambient [1]	1440	320	47.1
ambient [1]	2880	333	44.4
boiling [2]	30	238	63.2
boiling [2]	60	245	73.1

1 - approximately 21 C 2 - approximately - 100 C

Conclusions - Osmotic dehydration will occur both at room and boiling temperatures, but is more efficient at boiling temperature. This is because the high heat treatment causes cellular disruption. Equilibrium is achieved by 24 hours at room temperature. At boiling temperature, there is a slight gain in solids content between 30 and 60 minutes. The advantage of removing excess water with high temperature might be offset by the heat damage to the product quality. Therefore, a study to optimize the temperature effect and to examine the protective effect of the solute on the heat damage would be useful.

C. Effect of forced air drying of cherries

Three hundred g of cherries were mixed with 600 g of 80% sucrose solution. Duplicate batches were gently boiled with constant mixing for 60 minutes. At the end, the cherries were separated from the syrup and rinsed. Both batches had additonal mosture removed by forced air drying for 2 hours at 82 C. The increase in solids content is shown in Table 3.

Table 3 - Solid Content of Cherries after 60 Minutes at Boiling Temperature and Forced Air Drying

Batch	Final Mass, g	Final Percent Solids
1	257	74.4
2	252	81.6

Conclusions - The results were similar to that in Part B where no subsequent drying was done. It shows that the conditions are reproducible and that subsequent air drying is not necessary , if not undesirable, when the osmosis occurs at boiling temperature.

D. Effect of processing temperature with blueberries.

This study duplicates the operating conditions of Part B but with blueberries. The increase in solid content is shown in Table 4. In each run 300 g of blueberries were used.

Table 4 - Solid Content of Blueberries as Function of Processing Temperature

Process Temp. C	Time, Min	Final Mass, g	Final Percent Solids
ambient [1]	1440	275	43.0
ambient [1]	2880	285	46.7
boiling [2]	30	181	56.0
boiling [2]	60	159	67.6

1 - approximately 70 C 2 - approximately 100 C

Conclusions - As with the cherries, boiling temperature was more efficient than room temperature. At ambient temperature there was little increase in solids content between 24 and 48 hours. There was an increase in solid content with boiling temperature between 30 and 60 minutes. It will therefore, depend on the final products intended. If the physical quality is not critical and the target nutrients are heat-stable, then a boiling process will be beneficial to remove water quicker and more efficiently. However, this case is rare and the treatment should be considered only when mild heat or vacuum osmosis is not possible.

E. Effect of forced air drying with blueberries

This study duplicates operating conditions of Part C but with blueberries. (300 g of fruit mixed with 80% sucrose solution and boiled for 60 minutes.) The increase in solid content is shown in Table 5. Three hundred g of blueberries were used.

Table 5 - Solid Content of Blueberries after 30 Minutes at Boiling Temperature and Forced Air Drying

Batch	Mass After Osmosis g	Percent Solids After Osmosis	Percent Solids After Air Drying
1	182	56.0	92.0
2	179	61.9	93.5

Conclusions - The forced air drying was at 82 C for two hours. This duplicates the third run of Part D. Although it took two separate treatments to achieve the final dry products, it would suffer less heat damage than the single boiling concentration.

F. Effect of batch size for blueberries

This study duplicates the conditions of Part E but with a batch size of 600 g of blueberries and 1200 g of osmotic solution. The increase in solid content is shown in Table 6.

Table 6 - Solid Content of Blueberries after 30 Minutes at Boiling Temperature and Forced Air Drying

Initial Mass g	Mass After Osmosis g	Percent Solids After Osmosis	Percent Solids After Air Drying
600	340	60.7	87.5

Conclusions - Doubling the batch size had no effect on the osmotic drying.

G. Effect of ratio of osmotic solution for blueberries

This study compares two quantities of osmotic solutions. The increase in solid content is shown in Table 7 The blueberries were gently boiled in the solution for 30 minutes. The batch size was 600 g.

Table 7 - Solid Content of Blueberries as Function of Ratio of Osmotic Solution to Fruit

Ratio of Osmotic Solution/Fruit	Final Mass g	Final Percent Solids
2/1	323	63.4
4/1	339	69.8

Conclusions - There was only a slight increase in efficiency by increasing the ratio. Therefore, for economical reasons, a lower ratio of osmotic solution to fruit is adequate.

H. Effect of different carbohydrate osmotic solutions with blueberries

This study compares the drying efficiency of different carbohydrates in the osmotic solutions. The increase in solid content is shown in Table 8. Osmotic drying was at boiling temperature for 30 minutes and forced air drying was two hours at 82 C. An initial mass of 300 g of blueberries, a 50% solids osmotic solution and a ratio of two parts osmotic solution to one part fruit was used.

Table 8 - Solid Content of Blueberries as Function of Different Carbohydrate Osmotic Solutions

Species in Osmotic Solution	Final Mass, g	Percent Solids	
		Before Air Drying	After Air Drying
Sucrose	218	45.4	86.0
Fructose	232	49.6	85.1
Dextrose	232	46.9	86.6
Maltodextrin	181	28.9	65.0

Conclusions - Sucrose, fructose and dextrose all had about the same efficiency. Maltodextrin did not work well at all. Fifty percent osmotic solution was not as efficient as the previous experiments at 80%. The choice of sweeteners can be made by considering whether the degree of sweetness is critical.

I. Effect of maltodextrin as osmotic solution with carrots

This study used an osmotic solution of 50% maltodextrin to dehydrate carrots. Four hundred and eighty g of carrots were used in contact with 960 g of the solution. Dehydration was done at boiling temperature for 30 minutes. It was followed by a final forced air drying for 2 hours at 82 C (180 F). The increase in solid content is shown in Table 9.

Table 9 - Solid Content of Carrots after Osmosis with Maltodextrin Solution

Final Mass	Final Percent Solids	
g	Before Air Drying	After Air Drying
376	33.6	73.1

Conclusions - Maltodextrin did accomplish more drying of the carrots than it did with the blueberries. The large molecule of maltodextrin would have more difficulty in penetrating through the waxy coating of the blueberries than it did with the carrots.

J. Effect of vacuum infusion and different osmotic carbohydrate solutions with cherries

This study used different carbohydrates in the osmotic solutions. The infusion was done under vacuum. The batch size was 300 g of cherries with 600 g of 80% solution. The increase in solid content is shown in Table 10.

Table 10 - Solid Content Oo Cherries after Vacuum Infusion

Species in Osmotic Solution	Time of Infusion Min	Final Mass g	Final Percent Solids
Sucrose	30	184	40.6
Sucrose	60	243	55.2
Fructose	30	193	34.2
Fructose	60	228	64.9
Dextrose	30	180	45.6
Dextrose	60	177	48.4
Honey	30	181	33.1
Honey	60	206	58.3

Conclusions - Vacuum infusion does work. Although it is not as efficient as sucrose at atmospheric pressure and boiling temperature there is no heat involved and therefore, the product quality will be well retained. Sixty minutes is more efficient than 30 minutes processing time. The relative efficiency of the sweeteners is that fructose is better than sucrose which is better than dextrose, after 60 minutes. Honey is slightly better than sucrose, but less than fructose

K. Effect of vacuum infusion and different osmotic carbohydrate solutions with carrots

This study used different substances in the osmotic solutions. The infusion was done under vacuum. The batch size was 300 g with 600 g of 50% solution. (The NaCl did not completely dissolve so the solution was at equilibrium concentration.) The increase in solid content is shown in Table 11.

Table 11 - Solid Content of Carrots after Vacuum Infusion

Species in Osmotic Solution	Time of Infusion Min	Final Mass g	Final Percent Solids
Sucrose	30	232	22.9
Sucrose	60	266	33.0
Honey	30	235	23.7
Honey	60	251	27.7
Maltodextrin	30	198	21.2
Maltodextrin	60	209	21.3
NaCl	30	242	24.7
NaCl	60	256	26.9

Conclusions - Vacuum infusion did work but not as efficiently as at atmospheric pressure and boiling temperature. Sixty minutes infusion time was slightly better than 30 minutes. Maltodextrin was not as efficient as the other osmotic species.

L. Caffeine infusion into blueberries with osmotic drying

This study examined the effect of infusion of caffeine into blueberries during osmotic drying. Three hundred g of blueberries were mixed with 600 g of 80% sucrose solution that contained caffeine. The mixtures were boiled for 30 minutes. The final caffeine content of the blueberries was determined in triplicate with HPLC methods. The results are shown in Table 12.

Table 12 - Caffeine Content of Blueberries After Osmotic Drying

Percent Caffeine in Sucrose Solution	Final Conc. µg/ml	Percent Uptake	Final Mass g	Final Percent Solids
0.083	558	84.9	199	65.6
0.166	1257	100.0	226	60.3

Conclusions - Caffeine will infuse very efficiently during osmotic dehydration at boiling temperature. The final solids content duplicated the earlier study.

M. Caffeine infusion into carrots with osmotic drying

This study examined the effect of infusion of caffeine into carrots during osmotic dehydration. Three hundred g of carrots were mixed with 600 g of 50% maltodextrin solution that contained caffeine. The mixtures were boiled for 30 minutes. The final caffeine content of the carrots was determined in triplicate with HPLC methods. The results are shown in Table 13.

Table 13 - Caffeine Content of Carrots after Osmotic Drying

Percent Caffeine in Sucrose Solution	Final Conc. µg/ml	Percent Uptake	Final Mass g	Final Percent Solids
0.083	665	85.8	267	43.6
0.166	1220	92.2	270	37.0

Conclusions - Caffeine will infuse very efficiently during osmotic dehydration at boiling temperature. The final solids content duplicated the earlier study. Further studies of atmospheric and vacuum infusion without boiling should be conducted to optimize the final product quality.

Discussion and Results

Osmotic dehydration will work very efficiently under a wide variety of conditions with many different products. The most favorable osmotic species is sucrose. Boiling temperature at atmospheric pressure worked best at the conditions studied. Osmotic dehydration can also be used to infuse nutrients into the product. Caffeine was used as a marker to demonstrate this. Although we demonstrated that vacuum infusion did induce some osmotic dehydration, it achieved only limited success. It might be more useful to subject osmotically dried products to the vacuum chamber and infuse these products with target solutes or nutrients.

Recommendations

More work needs to be done to quantify the drying and diffusion rates with different osmotic substances. Studies should also continue with other possible products. Combination drying processes should be studied to determine the most efficient way to achieve a shelf-stable final product.

This document reports research undertaken
at the U.S. Army Soldier Systems Command,
Natick Research, Development and Engineering
Center and has been assigned
No. NRDEC/TR-95/034 in the series of reports
approved for publication

REFERENCES

Adambounou, T. L., Castaigne, F., and Dillon J. C., 1983. Abassement de l'activite de Lleau de legumes tropicaux par deshydratation osmotique partielle. Sciences des Aliments. 3: 551

Adambounout, T. L. and Castaigne, F., 1983. Deshydratation partielle par osmose des bananas et determination de courbes de sorption isotherme. Lebensm.-Wiss.-Technol. 16:230

Andreotti, R., Tomasicchio, M. and Macchiavelli. L. 1983. Disidratazione parziale della frutta per osmosi. Industria Conserve. 58: 90

Barret, A.H., 1986. Maximizing caloric density by vacuum infusion of porous foods. Activities Report of the R&D Associates 38: 56

Barrett, A.H., 1987. Factors determining the infusion of suspended particulates into porous food matrices. Activities Report of the R&D Associates 39: 154

Barrett, A.H., Ross, E.W. and Taub, I.A., 1990. Simulation of the vacuum infusion process using idealized components: Effects of pore size and suspension concentration. J. of Food Sci., 55: 989

Biswal, R. N., Bozorgmehr, K., Tompkins, F. D. and Liu, X., 1991. Osmotic concentration of green beans prior to freezing. J. of Food Sci., 56: 108

Biswal, R. N. and Le Maguer, M. Mass transfer in plant materials in aqueous solutions of ethanol and sodium chloride: Equilibrium data., 1989. J. Food Proc. Eng. 1: 149,

Bolin, H. R., Huxsoll, C. C., Jackson, R. and NG, K.C., 1983. Effect of osmotic agents and concentration on fruit quality. J. Food Sci. 48: 202

Briggs, J. L., Dunne, C.P., Graham, M.A. Risvik, E., Cardello, A., Barrett, A. and Taub, I.A., 1986. A calorically dense ration for the 21st century. Army Science Conference Proceedings, West Point, NY 1: 81

Chandrasekaran, S. K. and King, J. C. Multicomponent diffusion and vapor-liquid equilibria of dilute organic components in aqueous sugar solutions, 1972. A.I.Ch. E. J 18: 513

Contreras, J. E. and Smyri, T. G. An evaluation of osmotic concentration of apple rings using corn syrup solids solutions., 1981. Can. Inst. Food Sci. Technol. J., 14: 310

Conway, J., Costaigne, F., Picard G., and Vovan, X. Mass transfer consideration in the osmotic dehydration of apples, 1983. Can. Inst. Food Sci. Techn. 16: 25

REFERENCES (Continued)

Dalla Rosa, M., Pinnaiva, G., and Lerici, C. R., La disidratazione della frutta mediante osmosi diretta. Nota II Esperienze de Laboratorio su Alcuni Generi di Frutta, 1982. Industrie Consserve. 57: 3

Dixon, G. M., Jen, J. J. and Paynter, V. A. Tasty apple slices result from combined osmotic dehydration and vacuum drying process, 1976. Food Prod. Dev. 10: 60

Farkas, D. F. and Lazar, M. E., Osmotic dehydration of apple pieces: Effect of temperature and syrup concentration on rates, 1969. Food Tech., 23, 688,

Flink, J. M. Dehydrated carrot slices: Influence of osmotic concentration on drying behavior and product quality, 1980. In *Food Process Engineering*, Vol. 1, 412, P. Linko, Y. Malkki, J. Olkku and J. Larinkari (Ed.), Academic Press, London

Giangiacomo, R., Torreggiani, D. and Abbo E. Osmotic dehydration of fruit: Sugar exchange between fruit and extracting syrup, 1987. J. Food Proc. Preserv., 11 (3) 183

Hawkes, J. and Flink, J. M. Osmotic concentration of fruit slices prior to freeze dehydration, 1978. J. Food Proc. and Pres. 2: 265

Huxsol, C. C. Reducing the refrigeration load by partial concentration of foods prior to freezing, 1982. Food Technol., 36: 98

Islam, M. M. and Flink, J. M. Dehydration of potato. II. Osmotic concentration and its effect on air drying behavior. 1982. J. Food Technol. 17: 387

Lenhart, A. and Flink, J. M. Osmotic concentration of potato. I. Criteria for the end point of the osmosis process, 1984. J. Food Technol. 19: 45

Lerici, C. R., Dalla Rosa, M and Pinnavaia, G. Direct osmosis as pretreatment to fruit drying. In Proc. of the 2nd European Conference on Food Chemistry, 1983. 287, Roma

Lerici, C. R., Pepe, M. and Pinnavaia, G. La disidratazione della frutta mediante osmosi diretta. I. Risultati di Esperienze Effetuate in Laboratirio, 1977. Industria Conserve. 52: 125

Lerici, C. R., Pinnavaia, G., Dalla Rosa, M. and Mastrocola, D. Applicazione dell osmosi diretta nella disidratzaione della frutta, 1983. Industrie Alimentari. 3: 184

Lerici, C. R., Pinnavaia, G., Dalla Rosa, M. and Bartolucci, L. Osmotic dehydration of fruit: Influence of osmotic agents on drying behavior and product quality, 1985. J. of Food Sci., 50: 1217

Kim, M. H. and Toledo, R. T. Effect of dehydration and high temperature fluidized bed drying on properties of dehydrated rabbiteye blueberries, 1987. J. of Food Sci., 52: 980

REFERENCES (Continued)

Madarro, A,, Carbonell, J. V., Pinaga, F. and Pena, J. L. Dehydration of fruit and vegetables with ambient air. Results of a series of experiences, 1983. In Proc.of the 6th Inter. Cong. of Food Sci. and Technol. 1: 104. Ed.: McLoughlin, J. V. and McKee, B. M., Booie Press, Dublin

Maltini, E., Torregiani, D., Bertolo, C. and Stecchini, M. Recent development in the production of shelf-stable fruit by osmosis, 1983. In Proc. of the 6th Inter. Cong. of Food Sci. and Technol. 1: 177, . Ed. McLaughlin, J. V. and McKee, B. M. Booie Press.Dublin

Pinnavaia, G., Dalla Rosa, M. and Lerici, C. R. La disidratazione mediante osmosi diretta per la valorizzazione di prodott vegetali, 1983. In Atti 2^{o} Convegno Nazionale Nutrizione, Ambiente, Lavoro. 313, Ed. Cocchi, M. and Tonini, G., Modena,

Ponting, J. D. Osmotic dehydration of fruits. Recent modifications and applications. Progress in Biochem, 1978. 8 (12), 18

Ponting, J. D., Watters, G. G., Torrey, R. R., Jackson R. and Stanley, W. L. Osmotic dehydration of fruits, 1966. Food Tech., 20: 1365

Ray, P. M. On the theory of osmotic water movement, 1960. Plant Phys. 35: 783

Torreggiani, D., Forni, E. and Rizzolo, A. Osmotic dehydration of fruit. Part 2: Influence of osmosis time and the stability of the processed cherries, 1987. J. Food Proc. Preserv. 12: 27

Torreggiani, D., Maltini, E., Bertolo, G., and Mingardo, F. Frozen intermediate moisture fruits: Studies on techniques and product properties, 1988. Proceedings of the International Symposium on Progress in Food Preservation Processes, Vol. 1, p. 71. CERIA, Brussels, Belgium

Yang, Angela, P. P., Wills, C. and Yang, T. C. S. Use of a combination process of osmotic dehydration and freeze drying to produce a raisin-type lowbush blueberry product, 1987. J. of Food Sci., 52: 1651